The International Journal Of Engineering And Science (IJES)
|| Volume || 3 || Issue || 10 || Pages || 69-76 || 2014 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Design Construction, Simulation and Testing of A 300W Wind-Powered Battery Charger

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ABSTRACT
This paper reports the design construction, simulation and testing of a 300W wind battery charger. The design was carried out based on long term available wind data for Jos at 10m height. The average wind speed for Jos is 5.24m/s and rated turbine wind speed is 6.29m/s. The designed components of the system were carefully constructed in a well-equipped workshop. The system was coupled and installed at a height of about 22m. The system was test run and the results recorded for a period of time on two consecutive days. A second degree polynomial was used to model the system power output between cut in and rated wind speeds. The calculated outputs were compared with the actual outputs and a root mean square error of 8.98% was found, showing that the closeness of fit of the calculated outputs to the actual characteristics of the wind-powered turbines is satisfactory. The average system efficiency between cut-in and rated wind speeds was determined to be 38.16%.

Date of Submission: 28 January 2014 — Date of Publication: 20 October 2014

I. INTRODUCTION

Wind Energy is energy contained in the force of the winds blowing across the earth's surface. When harnessed, wind energy can be converted into mechanical energy for performing work such as pumping water, grinding grain, and milling lumber. By connecting a spinning rotor (an assembly of blades attached to a hub) to an electric generator, modern wind turbines convert wind energy, which turns the rotor, into electrical energy[1]. Although wind is one of civilization's oldest forms of mechanical power, it suffered something of a relapse from the start of the past century as benefits of mass cheap energy supply came true. But as the true (and horrendous) cost of mass fossil fuel use came into light, wind is making a bid comeback, particularly with large grid connected turbines in europe [2]. A growing number of countries, Nigeria inclusive, are doing their best to encourage wind energy generation as part of a range of vital measures towards sustainability.

In addition, the electricity grid can provide households and communities with reliable, high quality, predictable and cheap electricity, but this is far from the norm for the majority of the world's population. Whilst being in the forefront of many government-stated development objectives, widespread electrification is still the dream rather than the reality for most. There is practically insufficient power supply in Nigeria, and even the little available is epileptic and inconsistent, yet the exponential growth in its demand is consistent. In areas without the grid, and areas with such undependable power supply, some households use motorcycle, car or lorry batteries to power their homes and power appliances. Wind energy battery charging systems become a very good alternative in such situations. With growing awareness and demand for the preference of renewable energy by international environmental organisations, the application of wind energy for battery charging will contribute to the cause. Every renewable energy system installed means reduction in a potential increase of greenhouse gas emissions.

This paper is on the development of a wind battery charging system. This would supply alternative battery charging when the wind is blowing despite fluctuating conventional power supply and will demonstrate the potential for the availability of wind battery charging systems and workshops in remote areas that are not connected to the electricity grid.This work will focus on designing, constructing, simulating the output and testing of a 300W wind battery charger. The design is for optimum operation in Jos, Nigeria. Jos is located on latitude 80°24'N and between longitude 80°32'E and 100°38'E. The altitude of Jos is about 1250 m (about 4100 ft) above sea level on the Delimi River, with average monthly temperatures ranging between 21° and 25° C **[1]**.

Jos has one of the best wind energy potentials in Nigeria [3]. At present, there is only one known electricity generating wind turbine in Jos, and even that system was not designed for the location. It was simply bought and installed, and would therefore not perform optimally. This project would present this potential in realistic terms, and could encourage the practice of wind energy generation to a reasonable extent in Jos in particular and Nigeria in general.

II. BASIC THEORY

The available power in wind, *P*, can be expressed as [4]:

$$P = {}^{1}/_{2}\,\rho A V^3 \quad (1)$$

The wind power per unit area, P/A or wind power density is:

$$P/A = {}^{1}/_{2}\,\rho V^3 \quad (2)$$

where

$\rho =$ density of air. At sea level (15^0C) = 1.225 kg/m^3
A = the area swept by the rotor
V = wind velocity.

Wind turbine rotor performance is usually characterised by its power coefficient, C_P[4]:

$$C_P = P_r \big/ {}^{1}/_{2}\,\rho A V^3 \quad (3)$$

Where,P_r = rotor power

The non-dimensional power coefficient represents the fraction of power in the wind that is extracted by the rotor. The maximum theoretically possible rotor power coefficient,$C_{Pmax} = 0.5926$.

The overall turbine efficiency,$\eta_{overall}$, is a function of both the rotor power coefficient and the mechanical (including electrical) efficiency, η_{mech}, of the wind turbine [4]:

$$\eta_{overall} = \frac{P_{out}}{{}^{1}/_{2}\,\rho A V^3} = \eta_{mech} C_P \quad (4)$$

Thus:

$$P_{out} = {}^{1}/_{2}\,\rho A V^3 \eta_{mech} C_P \quad (5)$$

Where P_{out} = generator power output

The variation in wind speed at a particular site can be best described using the Weibull distribution function, which illustrates the probability of different mean wind speeds occurring at a site during a period of time. The probability density function of a Weibull random variable $\bar{u}$is [5]:

$$f(x) = \begin{cases} \frac{k}{\lambda sf}\left(\frac{\bar{u}}{\lambda sf}\right)^{k-1} \exp\left(-\left(\frac{\bar{u}}{\lambda sf}\right)^{k}\right) & \bar{u} \geq 0 \\ 0 & \bar{u} < 0 \end{cases} \quad (6)$$

where λsf is the scale factor which is closely related to the mean wind speed and *k* is the shape factor, which is a measurement of the width of the distribution. As an example, the Weibull distributionsfor various mean wind speeds are displayed in Fig. 2

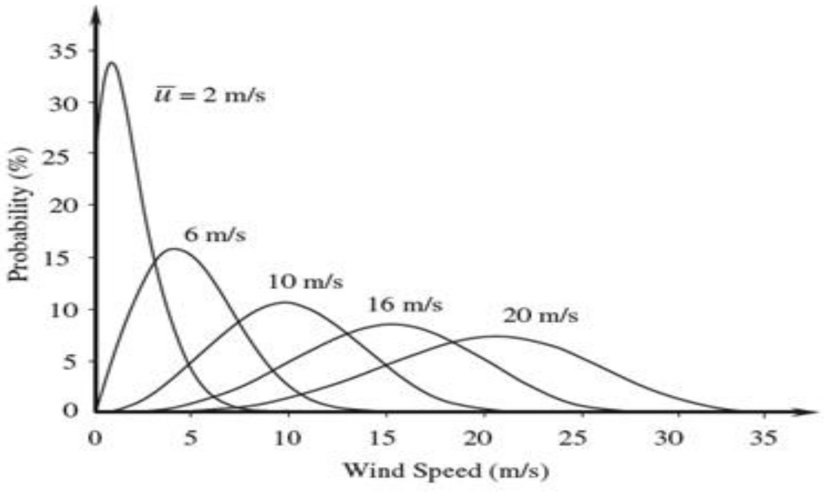


Figure 1: Weibull distributions for various mean wind speeds

III. MATERIALS AND METHODS

a. Description Of The Wind Turbine Generator

The wind turbine generator transforms the kinetic energy of the wind into mechanical energy, and then into electricity. The system is made up of three rotor blades, connected to a shaft via a hub. The blades, hub and shaft rotate as a unit. The shafts are passed through bearings. The generator is a car alternator. The shaft going into the alternator and that coming from the rotor are joined with a gearing system to step up the rotational speed in the alternator. These features are shown in Fig.3. The turbine is pointed into the wind by rotating the nacelle about the tower, which is called "yaw control". This is achieved with the help of the tail vane. The turbine operates with the rotor positioned on the windward side of the tower, which is referred to as an "upwind rotor". The turbine will generally start producing power once the minimum required wind speed is exceeded. The amount of energy in the wind available for extraction by the turbine increases with the cube of wind speed; thus a 10% increase in wind speed means a 33% increase in available energy. However, a turbine can only capture a portion of this cubic increase in energy because power above the level for which the electrical system has been designed (referred to as the "rated power") is allowed to pass through the rotor. The power produced by this generator is used to directly charge a battery.

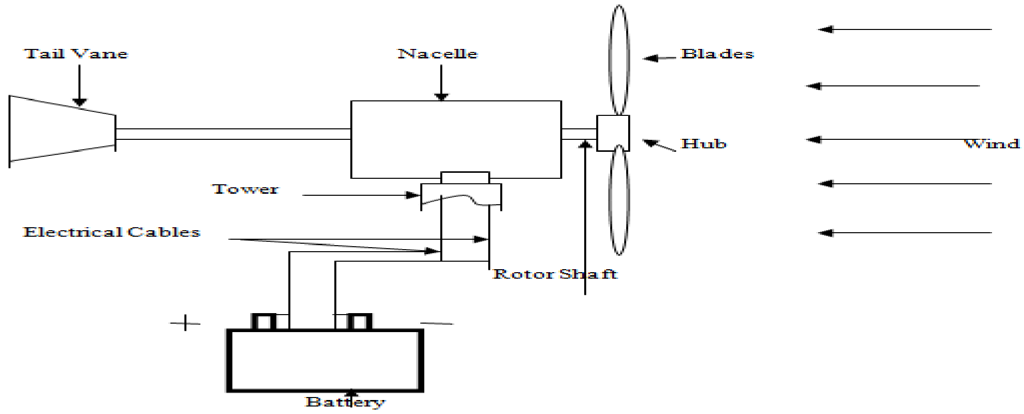


Figure 2: Schematic diagram of the wind battery charging system.

b. Materials

i. Materials Selection

A summary of materials used for this work is shown in Table 1 [4]

Table 1: Materials used in wind turbines

Subsystem or components	Material
Blades	White capara wood
Hub	Mild steel sheets
Shaft	Solid mild still rods
Gears	Tephlon
Nacelle	Metal sheets
Tail vane	Plywood
Tower	Hollow steel pipe

ii. Wind Speed Data

The main data used for the design is long-term observed wind speed data from surface anemometers. This observed wind speed data is available on request from the Nigerian Meteorological Agency (NMA), Oshodi, Lagos. Existing long-term meteorological wind speed data of various locations of the Northern Nigeria (Jos inclusive) that were available in Knots were collected by Pam [3]. The wind summary required for this design is average wind speed of the least windy month

c. Design Theories

i. Rotor Swept Area

The rotor swept area can be determined from equation (5). Thus:

$$A = {}^{2P_{out}}\!/_{\rho V^3 \eta_{mech} C_p} = \pi\, {}^{D^2}\!/_4 \qquad (7)$$

where, *D* is the rotor diameter.

ii. Tip Speed Ratio

The tip speed ratio is given by[4]:

$$\lambda = \frac{\pi}{30}\frac{R}{V}n_{rotor} \quad (8)$$

where, n_{rotor} is rotor speed in rpm, λ is the tip speed ratio, and R is the rotor radius. Typical choices for tip speed ratio and blade number for generator and pumps are shown in Table 3[2]

Table 2: Tip speed ratio for various wind turbines

Tip Speed Ratio	No. Of Blades	Functions
1	6-20	Slow pumps
2	4-12	Faster pumps
3	3-6	Dutch 4-bladed
4	2-4	Slow generators
5-8	2-3	Generator
8-15	1-2	Fastest possible

iii. Number of Blades

The number of blades used is largely dictated by the tip speed ratio. The choice can be made from table 1. The number of blades, *B*, can also be selected and rounded up from the following equation [2]:

$$B = 80/\lambda^2 \quad (9)$$

iv. Blade Profile

To achieve a good power coefficient, a blade profile that creates the optimum lift is needed, while minimising drag. In other words, the drag/lift ratio (drag divided by the lift) has to be minimised [2].

Wind tunnel studies show that the drag to lift ratio is not a constant factor. It varies with tilt of the section. The best ratio is usually at an angle of attack of around 4^0 [2].

v. Blade Setting Angle (β)

The blade setting angle (β) is the difference between the flow angle (ϕ) and the angle of attack (α). i.e:

$$\beta = \phi - \alpha \quad (10)$$

where ϕ is given by [2]:

$$\phi = \tan^{-1}(2R/(3r\lambda)) \quad (11)$$

vi. Blade Width or Chord (C_w)

The chord width, C_W, was calculated as follows[2]:

$$C_W = \frac{16\pi R\left(\frac{R}{r}\right)}{9\lambda^2 B} \quad (12)$$

vii. Blade Thickness

Thin sections have better drag/lift ratios, so they were used where for best performance. Near the root, where the speed ratio is low, the drag/lift is not so important, but the strength is. So, a thick section at the root wasused.

viii. Rotor Hub

The rotor hub was manufactured by cutting two metal sheets of thickness 2mm into the shape of the root of the rotor when the roots of the three blades are shaped to be 120 degrees apart. This also ensures that the leading edge of one blade is 120 degrees ahead of the subsequent one. Holes were drilled on both metal sheets on equivalent points as the blade roots. This allows the bolts to pass through the metal sheet in front, the blade root and the metal sheet behind, together forming the hub. A hole is drilled through the middle for mounting the hub onto the shaft.

ix. Tail Vane Design

The vane catches the wind, pulls on the boom, and swivels the machine about this yaw axis to face the wind. As a rule of thumb, the actual boom should be about equal to the length of one blade, i.e half of the rotor diameter, with a vane centred at its end. The vanes are rarely smaller than 3% (1/30th) of the swept area of the rotor. This is equivalent to [2]:

$$A_{vane} = D^2/40 \quad (13)$$

The tail vane was cut from plywood which makes a very durable vane.

x. Nacelle Housing

The nacelle was made up of a supporting table constructed by cutting metal sheet 300mm by 2.5mm, by 500mm long, a housing enclosing fabricated from sheet metals by shaping to form a three-dimensional box curved at the top. The casing support is provided by appropriate welding and joining angle iron and steel bars. Ventilation holes were made at the sides to allow air to circulate and cool the alternator and gears. A window was inserted for maintenance access whenever the need arises

xi. Tower Design

The tower can experience two major types of load: (1) steady and (2) dynamic [6]. Steady tower loads arise primarily from aerodynamically produced thrust and torque. The weight of the machine itself is also a significant load. The effects of loading must be considered especially on bending and buckling. The crippling or buckling load, W_{cr}, under various end conditions is represented by a general equation [6]:

$$W_{cr} = \frac{C\pi^2 EI}{L^2} = \frac{C\pi^2 EA{k_j}^2}{L^2} = \frac{C\pi^2 EA}{(L/k_j)^2} \quad (14)$$

where,

E = Modulus of elasticity or Young's modulus for the material of the column,
A = Area of cross-section,
k_j= Least radius of gyration of the cross-section, L = Length of the column, and
C = Constant, representing the end conditions of the column or end fixity coefficient.

Dynamic effects can be a significant source of loads, especially on soft or soft–soft towers. A stiff tower is one whose fundamental natural frequency is above the blade-passing frequency, a soft tower is one whose natural frequency is between the blade-passing frequency and the rotor frequency, and a soft–soft tower is one whose natural frequency is below both the rotor frequency and the blade-passing frequency. For either a soft or soft–soft tower, the tower can be excited during start-up or shutdown of the turbine. For the simple case, when the turbine/tower can be approximated by a uniform cantilever with a point mass on the top, the following equation may be used [4]:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{(0.23\, m_{Tower} + m_{Turbine})L^3}} \quad (15)$$

where f_n is the fundamental natural frequency (Hz), I is the moment of inertia of the tower cross-section, m_{Tower} is the mass of the tower, $m_{Turbine)}$ is the mass of the turbine, and L is the height of the tower.

d. Design Considerations

The following parameters were considered for the design:

- A mean annual wind velocity of 5.2m/s
- A generator rating of 300W was be used.
- Based on the studies carried out, the specific output of horizontal axis wind turbine is particularly dependent on the ratio of the rated speed $V_r$to the annual mean velocity V_m and independent of the wind velocity distribution over the earth. V_r / V_m= 1.2 which is within the important range, range of1 to 2 [7]
- A power coefficient of 0.40 was used. This is because the theoretical maximum of 0.593 [4] cannot be attained in practice.
- A tip speed ratio, λ, of six (6). This falls within the suitable tip speed ratio range for generators [2]
- Three (3) tapered blades were used. Thisis a suitable number for wind generators, and the choice of three provides more rotor balance than two [2].
- The blade profile was that of NACA 4412.
- An angle of attack of 4^0 for minimum drag/lift coefficient of about 0.8 [2].
- The 20° *full depth involute system* will be used for the gearing. The increase of the pressure angle from 14 /2° to 20° results in a stronger tooth, because the tooth acting as a beam is wider at the base.
- A service factor of two (2) would be used for the gear design for heavy shock and 24 a hour day operation.

e. Results Of Design Calculations

Results from the designed calculations are summarised below:

- Rated wind speed for the machine (V_r) = 6.29m/s
- Rotor swept diameter (D) = 2.5m
- The blade chord, C, at various radii, r, were: $C_{r=1.25}$= 0.06m, $C_{r=1.0}$= 0.08m, $C_{r=0.75}$= 0.11m, $C_{r=0.5}$= 0.16m, $C_{r=0.25}$= 0.32m

- The blade setting angle $\beta = 3.91^0$
- At rated speed and tip speed ratio of 6, Rotor speed (N) = 288.3 r.p.m
- Surface area of the tail vane $A_t = 0.24m^2$

f. Coupling & Finishing

The system components were manufactured such that they can be coupled into a single unit on installation. The nacelle, tail vane, tower and hub were painted with light green oil paint. The blades were first of all treated before painted with the same oil paint as the other components.

g. Installing And Testing The System

The various components were coupled together to form the 300 Watt wind turbine battery charging system.A picture of the system is shown in Fig.3. The tower was mounted on a cast concrete base and tightly held by four bolts cast together with the base. The wind speed, generator output current (A) and voltage are read on an anemometer, ammeter and a voltmeter respectively. The corresponding power output at a given wind speed, voltage and current was calculated and recorded.

Figure 3: The Coupled Wind Turbine

h. Simulation Of The Wind Turbine Power Output

To estimate the power output from a wind-powered turbine, knowledge of the power output function, *P(V)*, and the probability wind speed distribution are required.

i. Method Of Analysis

The power output function, *P(V)*, of the wind-powered turbine generator in terms of the cut-in speed, V_i and rated speed V_r is as follows [3]:

$$P(V) = \begin{cases} 0, & V \le V_i \\ A + BV + CV^2, & V_i < V \le V_r \\ P_r, & V_r \le V \le V_0 \end{cases} \quad (16)$$

This is assuming a quadratic variation of the power output with wind speed between cut-in and rated wind speeds. Where the wind speed is evaluated at the wind turbine hub height and *A,B and C* are coefficients that are determined by the following conditions:

$A + BV_i + CV_i^2 = 0$

$A + BV_r + CV_r^2 = P_r$

$A + BV_m + CV_m^2 = P_r (V_m/V_r)^3$

Where $V_m = (V_i + V_r)/2$

By employing Cramer's rule [6], A, B and Cfrom the above simultaneous equations can be shown to be:

$$A = \left[\left(\frac{V_m}{V_r}\right)^3 (V_i V_r^2 - V_r V_i^2) - (V_i V_m^2 - V_m V_i^2)\right] P_r / E \quad (17)$$

$$B = \left[(V_m^2 - V_i^2) - \left(\frac{V_m}{V_r}\right)^3 (V_r^2 - V_i^2)\right] P_r / E \quad (18)$$

$$C = \left[\left(\frac{V_m}{V_r}\right)^3 (V_r - V_i) - (V_m - V_i)\right] P_r / E \quad (19)$$

Where:

$$E = \left[(V_r - V_i)(V_m^2 - V_i^2) - (V_m - V_i)(V_r^2 - V_i^2)\right] \quad (20)$$

An error analysis could be carried out to test the "goodness-of-fit" of the stated assumptions made on the power output function between cut-in and rated wind speeds. If "*n*" actual power output values, P_a, from the wind-turbine generator (measured) are available in the range $V_i < V \leq V_r$ and the analysis yields calculated power outputs, P_c, within the same velocity range, then the percentage error, ε_j, between the actual and calculated power outputs at each of the *"n"* points is given by:

$$\varepsilon_j = \left(\frac{P_a - P_c}{P_a}\right)_j \times 100\,;\, j = 1,2,3 \ldots \ldots, n. \quad (21)$$

For the "n" values, the root mean square percentage error, $\bar{\varepsilon}$, is given by:

$$\bar{\varepsilon} = \sqrt{\frac{\sum_{j=1}^{j=n}\left[\left(\frac{P_a - P_c}{P_a}\right)_j \times 100\right]^2}{n}} \quad (22)$$

The rms percentage error, $\bar{\varepsilon}$, can be used as an index for the closeness of fit of the simulated power output to the actual power output from the wind-powered turbine.

ii. Simulation Data Analysis

The turbine has a cut-in wind speed $V_i = 3.56m/s$, rated speed $V_r = 6.29m/s$, and rated power $P_r = 300W$
Thus, the mean velocity, V_m, can be calculated as follows:

$$V_m = {(V_r + V_i)}/{2} = {(6.29 + 3.56)}/{2} = 4.93m/s$$

For a second degree power variation, inserting the values for V_r, V_i, V_m *and* P_r into equation (18) to equation (24), the following values are obtained A = -317.87, B =77.63, and C = 3.27
Hence,

$$P(V) = -317.87 + 77.63V + 3.27V^2 \quad (23)$$

Equation (224) is the simulation equation of the power output as a function of wind speed between cut-in and rated wind speeds. This was used to obtain the calculated power output.

i. Efficiency

Zaria has an altitude of 653.9m above sea level and therefore a corresponding air density of 1.147kg/m^3 [3]. The overall efficiency, from equation (4) is given by:

$$\eta_{overall} = \frac{P_{out}}{{1}/{2}\rho A V^3} \quad (24)$$

The overall power efficiency at each velocity recorded is calculated and tabulated in table 7

IV. RESULTS AND DISCUSSIONS

The actual power outputs and calculated power outputs are plotted and shown in Fig.4
The root mean square percentage error calculated from equation (24) is 8.98%
The actual power output and calculated power output are obtained from table 6 and plotted on the same graph shown in figure 9

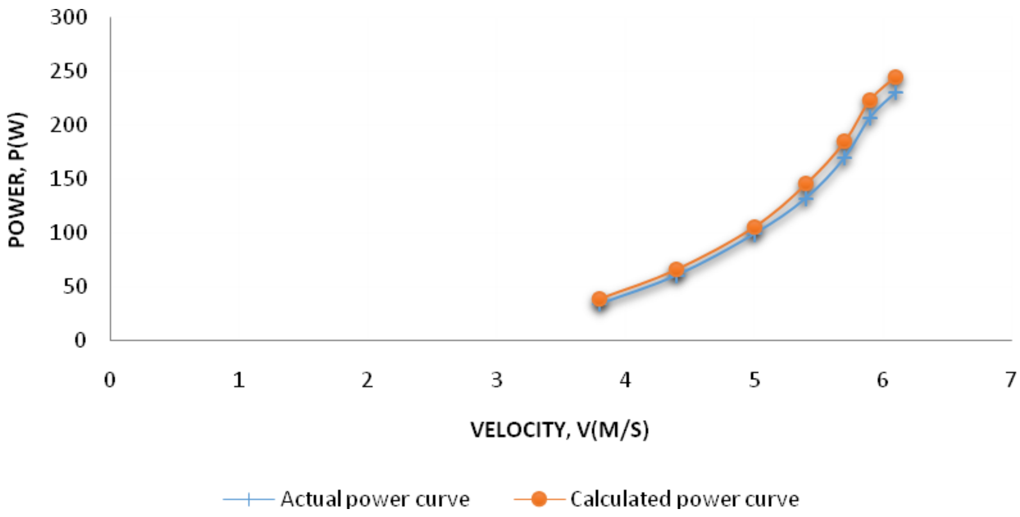
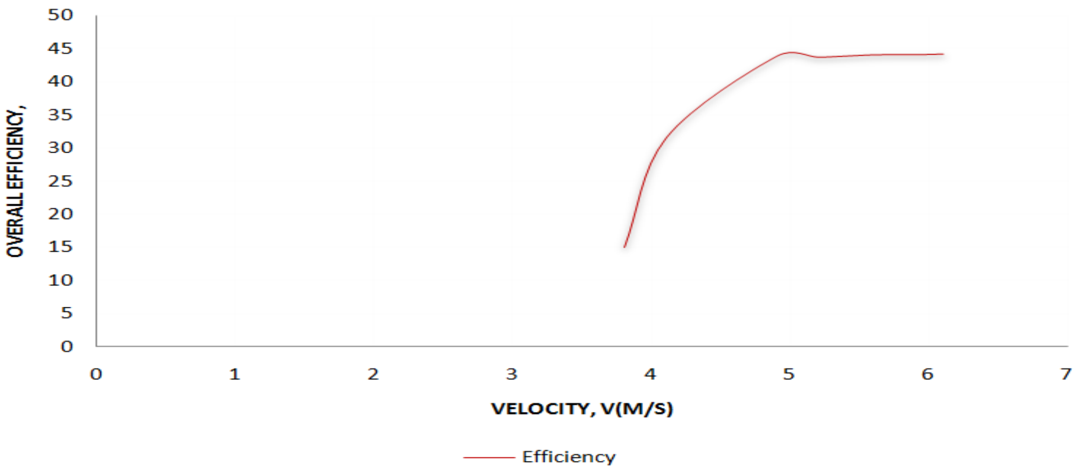


Figure 4: Actual and calculated power curves compared

Fig.4 shows a comparison between the actual power output curve and the simulated power output curve. The power available is a function of a cube of the velocity [8]. Therefore, the slopes of the curves are steep. These curves, which are for the power output between cut in wind speed and rated wind speed for the wind turbine, are similar in shape. This shows that using a second degree polynomial to model the system is satisfactory. It describes very well the nature of the system performance between the cut in wind speed and rated wind speed of the wind turbine.

The rms percentage error, $\bar{\varepsilon}$, is 8.98%. This is an indicator that the simulated power output or performance of the turbine is close enough to the actual power output, and shows further that the closeness of fit to the actual characteristics of the wind-powered turbines is satisfactory. The system was designed for the wind data of Jos, but tested in Zaria. This has significance in the observed output. The wind data for Jos is much more superior to that of Zaria [3]. This means the performance, if tested in Jos, would be better. This shows how important it is to design a wind turbine with the observed wind data of the location in which it will be used. The practice of buying any wind turbine in the market and installing it anywhere might seem to work, but in truth is not optimizing the wind data for that location. Locally designing and manufacturing turbines should be promoted.

The average overall efficiency is 38.16 %



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igure 5: Overall efficiency curve.

The overall efficiency curve behaves as expected. The efficiency increases with increase in velocity between cut in and rated wind speeds. Reason being that the power coefficient, C_P, increase with windspeed up to the design speed. As the wind velocity increases, the available power increases by the velocity cubed. This in turn increases the power output of the generator and hence the efficiency.

Thus, the highest efficiency of the wind turbine was 44.29% which occurred at the highest wind speed attained in the system operation. The average overall efficiency was found to be 38.16%, which is a very good result for a practical situation. Therefore if this system operates in a region with predominantly the rated wind velocity (6.29m/s), it would be practically very efficient most of the time.

V. CONCLUSIONS

i. A 300W wind energy battery charger was designed following strict design principles, constructed and tested.

ii. A simulation of the system performance output was carried out using a second degree polynomial model, and it showed that this model satisfactorily represents the actual system behavior between cut in and rated wind speeds, in view of the lowroot mean square percentage errors.

iii. The overall efficiency increases with increase in wind speed between cut-in and rated wind speeds.

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